REQUIREMENTS AND USE OF INDIRECT METHODS FOR ESTIMATING THE HYDRAULIC FUNCTIONS OF UNSATURATED SOILS

K. Bohne

University of Rostock, Germany

C. Nitsche

Groundwater Research Center, Dresden University of Technology, Dresden, Germany

Feike J. Leij

U.S. Salinity Laboratory, USDA, ARS, Riverside, California, USA

The solution of field-scale flow and transport problems requires accurate estimates of the unsaturated soil hydraulic parameters. Direct field and laboratory measurement of the hydraulic functions is time consuming and expensive. By comparison, indirect theoretical methods that predict the soil hydraulic functions from more easily measured soil texture data, organic matter content, bulk density and other data are more convenient. The accuracy and comparability of the predicted unsaturated soil hydraulic functions depends on the method used for measuring soil texture and related data. In this paper we discuss the need for developing an international database of measured soil hydraulic data as a function of soil type and the experimental methodology. The database should contain such information as the soil water retention function, the unsaturated hydraulic conductivity function, the particle-size distribution, bulk density, organic matter content, and related data. The hydraulic properties in the database must be obtained with internationally standardized procedures, equipment, and methods of analysis. Estimation of the unsaturated soil hydraulic parameters demands standardized software tools linked to a representative soil database of manageable size. Modeling of subsurface flow and transport often requires the transformation from point values to areal values of the hydraulic parameters. This may be done by including additional software for estimating the unsaturated soil hydraulic parameters in time and space.

INTRODUCTION

Since many reliable numerical models for simulating soil water flow are now available [*Campbell*, 1985; *Richter and Anlauf*, 1988], the accuracy of site-specific simulations increasingly hinges on the reliability of model parameters. Misleading results are easily obtained unless careful attention is given to the selection of the unsaturated soil hydraulic properties [*Scotter et al.*, 1988]. Model applications may include (i) detailed investigations of an experimental plot, (ii) assessments of hydrological or agricultural properties of watersheds or other large areas, and (iii) assessments of the hydraulic or mechanical properties of soil units, regardless of their location. For these applications, and for future use by researchers, it is beneficial if soil physical data, measured for a wide variety of soils, are easily accessible. This paper will discuss some of the problems associated with the development of a soil database, and the use of indirect methods to estimate parameters of soil hydraulic functions to be incorporated in such a database.

DEVELOPMENT OF A DATABASE OF SOIL PHYSICAL PROPERTIES

Results of soil physical measurements are scattered throughout the soil physics and hydrology literature. Experiments are generally carried out to meet specific objectives, and the results of such individual studies are therefore often too incomplete to be useful for others. To alleviate this problem, we recommend the development of a database of measured soil physical properties. Retrieving information from such a database is obviously far less time-consuming than collecting data from original literature sources. Also, additional information can readily be incorporated in the database to make the measurements more useful for application by others. Hence, the existence of such a database could potentially save a considerable amount of time and effort.

One of the main problems associated with the development of a soil database is the great diversity of experimental methods used in soil physics, hydrology, and related disciplines. Results obtained with different measurement methods are often not comparable. This point is illustrated in Figure 1, which compares measured particle-size distributions obtained with the sedimentation method (Bouyoucos hydrometer) to those obtained with an optical particle-size analyzer. The two curves are quite different, particularly for grain sizes between 0.006 and 0.06 mm. Differences such as those shown in Figure 1 may arise because of different measurement principles and/or different instrumental techniques [e.g., *Nitsche et al.*, 1992]. Hence, methods for indirectly estimating soil hydraulic properties from soil textural data [e.g., *Rawls and Brakensiek*, 1985] must account for differences in the experimental methodology. Soil texture data used to formulate the predictive regression equations for the water retention curve, may have been obtained with radically different methods than the textural data of the soil for which the water retention needs to be predicted.

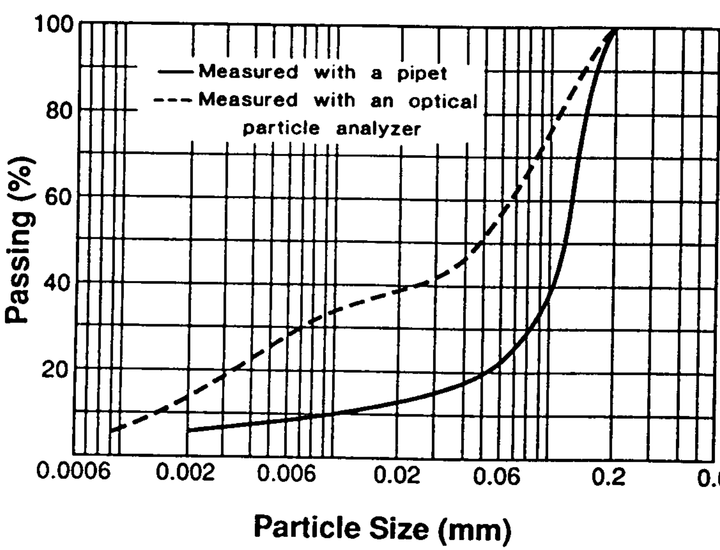


Fig. 1. Cumulative grain-size distribution for a loamy sand obtained with optical particle-size analysis and the sedimentation method.

Another important problem is that sample disturbance may substantially alter experimental results. For example, our experience is that sample disturbance can have a significant effect on the measured soil water retention curve. While these effects are most pronounced in the wet range, they may have an effect up to 3 bars pressure. In general, the degree of disturbance is highly variable since many factors are involved.

The above two problems point out the need for standardized methods of measurement, and for proper documentation of the methodology employed for obtaining the data before they can be included in the database. Because of the continuing development and use of theoretical models for predicting the soil hydraulic functions, it is imperative that measured hydraulic data be included in the database. Since such information by itself might not always suit the immediate needs of the user, the database should be accompanied by appropriate software for managing the information in the database. Figure 2 schematically illustrates the possible structure of database software for predicting water retention properties from particle size, bulk density, particle density, and organic matter content. The software must make it easier for users to extract selected information from the database for specific applications, as well as generate typical hydraulic curves or evaluate hydraulic parameters for specific soils. The user should be able to retrieve information from the database for analysis by a microcomputer for other applications.

The database ought to contain entries for textural class, sampling depth, soil classification unit, and geological and climatological conditions. Table 1 lists a number of soil physical properties which we believe must be included. The information can be useful for a large number of applications.

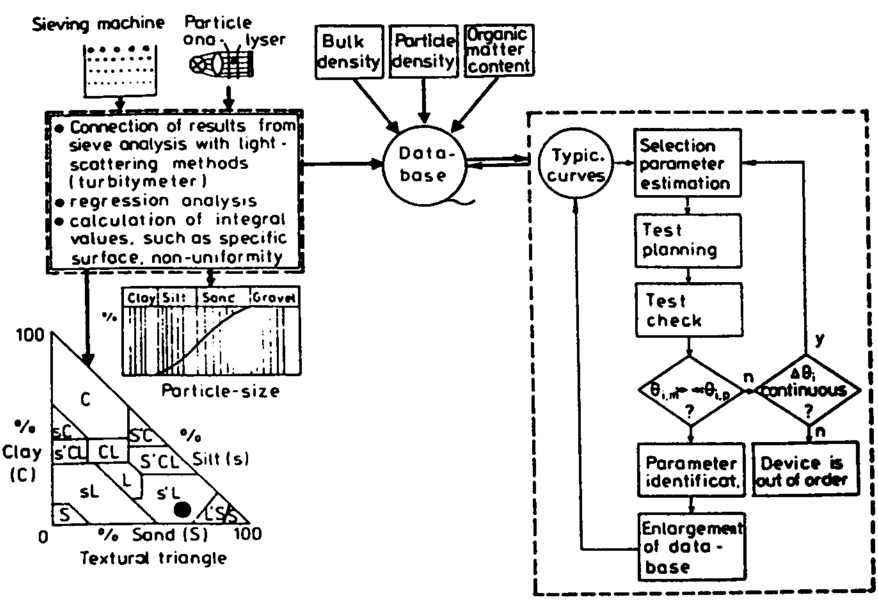


Fig. 2. Possible software structure for predicting water retention from basic soil data.

TABLE 1. Recommended Entries in a Database of Soil Physical Properties

1.	*Soil Composition and Soil Structure*
1.1	Dry bulk density as a function of compaction and wetness (Proctor test)
1.2	Actual dry bulk density
1.3	Particle density
1.4	Cumulative grain size distribution
1.5	Organic matter content
1.6	Clay mineralogy
2.	*Soil Hydraulic Properties*
2.1	Field-saturated (satiated) water content
2.2	Air-dry water content
2.3	Water content at a pressure head of 15,000 cm
2.4	Soil water retention data over a wide range of pressure heads, including hysteresis
2.5	Field-saturated (satiated) hydraulic conductivity
2.6	Vertical and horizontal saturated hydraulic conductivities
2.7	Measured unsaturated hydraulic conductivity data
3.	*Soil Mechanical Properties*
3.1	Shrinkage limit
3.2	Upper and lower plasticity limit; sticky limit
3.3	Shrinkage characteristics of swelling soils
3.4	Cohesiveness (saturated soil)
3.5	Angle of internal friction (saturated soil)
4.	*Soil Thermal Properties*
4.1	Thermal conductivity as a function of water content
4.2	Specific heat capacity as a function of water content

REQUIREMENTS AND ANALYSIS OF SOIL HYDRAULIC PARAMETERS

Parameter Estimation Using Direct Measurements

The evaluation of soil hydraulic parameters from water retention data, or from both water retention and hydraulic conductivity data, by least-squares techniques is well known [*van Genuchten*, 1980; *Kool et al.*, 1987]. Model parameters obtained in this way need further validation or adjustment before they can be used with confidence for simulating unsaturated water flow. This experimental validation is best achieved by flow experiments in the field. Theoretical predictions of the flow process, using the hydraulic parameters to be validated, are preferably done with analytical solutions to limit computer requirements. As an example, we consider the soil water sorptivity, S, which may be estimated from field data using the approximate solution by *Philip* [1969] for infiltration, i.e.,

$$I = S\sqrt{t} \tag{1}$$

where t is time, and I is the cumulative infiltration rate. A theoretical value for S can be obtained by using the expression by *van Genuchten* [1980] for the soil water diffusivity, D, as predicated by the conductivity model of *Mualem* [1976] and the retention model by van Genuchten:

$$S = \sqrt{2\Phi\Delta\theta} \tag{2}$$

where

$$\Phi = \int_{\theta_i}^{\theta_s} D(\theta)\, d\theta \tag{3}$$

$$D = \frac{K_s S_e^{\ell - 1/m}(A^{-1} + A - 2)}{\alpha(\theta_s - \theta_r)(n-1)} \tag{4}$$

in which

$$\Delta\theta = \theta_s - \theta_i \tag{5}$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{6}$$

and

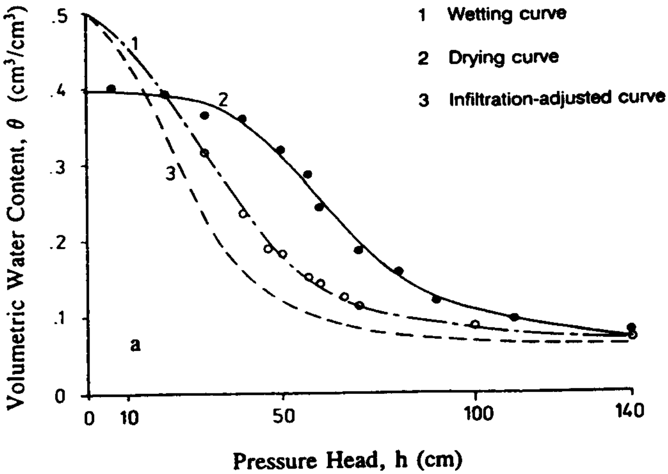
$$A = (1 - S_e^{1/m})^m \tag{7}$$

In these equations, θ is the volumetric water content; θ_r, θ_s, and θ_i are the residual, saturated, and uniform initial water contents, respectively; S_e is effective saturation; K_s is the saturated hydraulic conductivity; ℓ is an exponent often set to 0.5; and α, n, and m are constants in the water retention model of *van Genuchten* [1980]:

$$S_e = [1 + (\alpha h)^n]^{-m} \qquad (m = 1 - 1/n) \tag{8}$$

where h is the soil-water pressure head.

The soil hydraulic parameters in (4) can be adjusted so that the predicted value for S (Eq. 2) matches the field-measured value (Eq. 1). An example of this procedure was carried out using infiltration measurements obtained by *Scotter et al.* [1988]. Results are given in Table 2 and Figure 3. The open and closed circles in Figure 3 denote experimental points for the wetting and drying curves, respectively. We first fitted the hydraulic parameters of the van Genuchten and Mualem models simultaneously to experimental data of the wetting branches of the water retention, $\theta(h)$, and hydraulic conductivity, $K(\theta)$ curves. Values of the model parameters are listed in Table 2. Although $\theta(h)$ and $K(\theta)$ were described reasonably well, the infiltration was predicted poorly with the hydraulic parameters obtained from fitting the hydraulic data. Next, we obtained adjusted hydraulic parameters by fitting the previous stated models for infiltration and water retention simultaneously to the experimental data. In this case the infiltration could be fitted reasonably well with the resulting parameters, but the hydraulic properties were described poorly as shown in Figure 3.



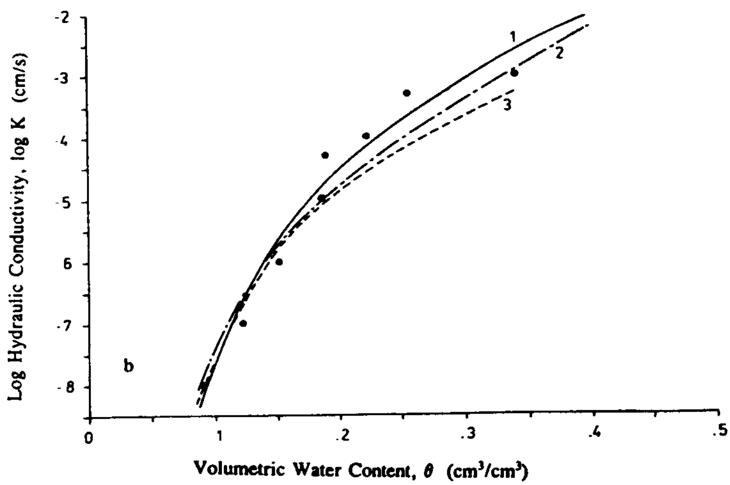


Fig. 3. Hydraulic properties measured by *Scotter et al.* [1988]: (*a*) water retention, and (*b*) unsaturated hydraulic conductivity.

It should be noted that somewhat better results might have been possible if a numerical solution of the flow equation were used in the inverse problem as outlined by *Mishra and Parker* [1989]. Because this approach requires a relatively high computational effort, we decided to use the more convenient analytical solution.

TABLE 2. Parameter Values of the Mualem and van Genuchten Models for the Hydraulic Properties for Data Obtained by *Scotter* [1988]

	Process	θ_r	θ_s	α	n	ℓ	K_s
		---cm^3	cm^{-3}---	cm^{-1}			cm s^{-1}
1	Drying	0.05	0.395	0.0170	4.44	3.76	8.42×10^{-3}
2	Wetting	0.05	0.483	0.0340	3.06	2.53	1.15×10^{-2}
3	Adjusted for infiltration	0.05	0.483	0.0475	3.06	2.53	8.42×10^{-3}

It is our experience, as well as that of many others, that similar water retention curves can be obtained with quite different sets of parameter values. This shows that the use of least-squares methods may not retain the physical meaning of the model parameters. Also, a small change in one of the parameters can sometimes significantly alter the predicted retention curve. As an example, we investigated the influence of small changes in the hydraulic parameters on the pressure head profile during steady-state capillary rise from a water table. The pressure head was obtained numerically from Darcy's law according to

$$z(h) = \int_0^h \frac{dh}{1 + q/K(h)} \tag{9}$$

where $K(h)$ is the unsaturated hydraulic conductivity function as a function of h, q is the upward water flux, and z is the distance above the water table.

Table 3 gives the values of the parameters α and n, which were obtained with the nonlinear least-squares optimization code RETC of van Genuchten as described by *Leij et al.* [1992]. This program also provides 95% confidence limits for the parameter estimates.

The values for the different limits of α and n, as shown in Table 3, were used to calculate pressure head profiles with Eq.(9). Figure 4 shows the resulting $z(h)$ profiles. The results of this example indicate that parameter values which appear statistically equivalent may lead to different simulation results.

TABLE 3. Mean, Upper, and Lower Confidence Values for α and n as Obtained with RETC for the Sandy Loam Listed in Table 4 (No. 7)

Data Set No.	α cm^{-1}	Confidence limit	n	Confidence limit
1	0.0538	mean	1.215	mean
2	0.0538	mean	1.248	upper
3	0.0538	mean	1.182	lower
4	0.0807	upper	1.215	mean
5	0.0269	lower	1.215	mean
6	0.0807	upper	1.248	upper
7	0.0807	upper	1.182	lower
8	0.0269	lower	1.182	lower
9	0.0269	lower	1.248	upper

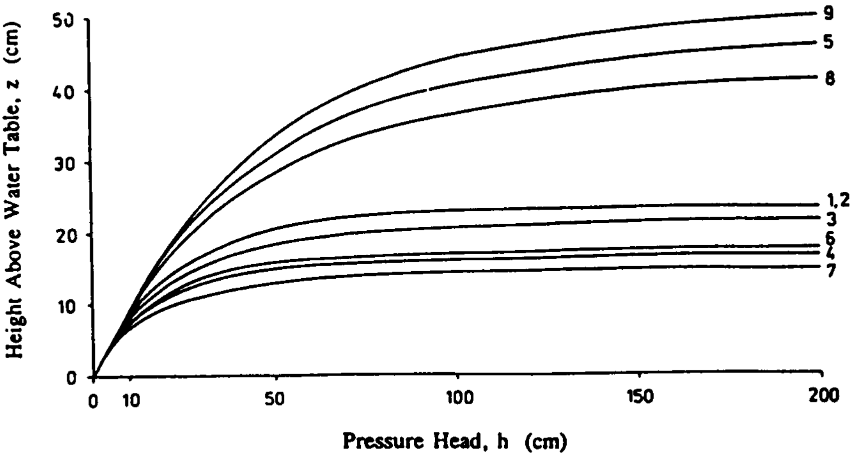


Fig. 4. Pressure head profiles for steady-state capillary rise from the ground water table calculated with the values for α and n shown in Table 3 and $\theta_r=0$, $\theta_s=0.351$, $\ell=0.5$, and $K_s=20$ cm/d.

Rapid Characterization of the Soil Hydraulic Parameters

Many studies of soil water flow, especially for large areas, require expedient but low-cost methods for obtaining the unsaturated soil hydraulic properties. Reduced accuracy of the parameters is only acceptable if soil properties across the larger area exhibit more variability as compared to a relatively small area for which one may be inclined to use more elaborate and hence time-consuming methods. In many instances this is not the case. Therefore, it is important to know the range of the variogram function and the standard deviation of scaling factors for the relevant soil physical properties.

A variety of relatively simple methods exists to estimate the soil hydraulic parameters functions from other soil properties with regression equations [*Bloemen*, 1980; *Vetterlein*, 1983; *Rawls and Brakensiek*, 1985; *Wösten and van Genuchten*, 1988]. Simulation results obtained with hydraulic functions derived from basic soil properties are particularly susceptible to error because hydraulic parameters may lose their physical meaning during the indirect estimation procedure. Furthermore, there usually is no unique solution for the parameter estimation problem and the flow model remains sensitive to changes in the parameter values. Instead of using single parameter estimation procedures, it is probably better to obtain soil hydraulic parameters using joint statistical analyses such as those presented by *Carsel and Parrish* [1988].

Alternatively, soil hydraulic functions could be obtained also from a set of typical curves. Each of these curves is represented by a parameter set which has been proven to yield reliable results. Characteristic parameter sets ought to be derived from the type of database we referred to earlier. On the basis of integral soil hydraulic properties (e.g., the matrix flux potential), it is then possible to formulate classes of hydraulic properties, with each class having its own characteristic set of parameter values. Errors due to model sensitivity and splitting up data sets into, for instance, retention and conductivity data, will be minimized in this manner.

Table 4 contains hydraulic parameter sets for a variety of German soils based on characteristic retention data compiled by *Vetterlein* [1989]. The hydraulic parameters were obtained with the RETC program using the water retention function of *van Genuchten* [1980]. The soil texture classes and genetic horizons in Table 4 represent the agriculturally most important soils in eastern Germany. We have used the east German system of texture classification and horizon labeling. The data are part of a larger data set collected for 61 soils. Additional information is available to approximate the saturated hydraulic conductivity, K_s, on the basis of soil structure and soil texture [*Vetterlein*, 1990]. Using the conductivity model by *Mualem* [1976], i.e., $\ell=0.5$, and the retention model of *van Genuchten* [1980] the hydraulic functions can now be quantified for the most important soil units in eastern Germany.

TABLE 4. Soil Hydraulic Parameters of the van Genuchten Model for Retention Data by *Vetterlein* [1989] for Selected Subsoil Horizons

No.	Texture class	Horizon	θ_s	θ_r	α	n
			------cm^3/cm^3------		cm^{-1}	
1	Medium Sand	C, G, B	0.373	0.0304	0.0363	3.03
2	Fine Sand	C, G	0.386	0.0361	0.0251	3.55
3	Slightly Loamy Sand	C	0.339	0.0405	0.0599	1.51
4	Slightly Loamy Sand	Bv	0.362	0.0385	0.0793	1.48
5	Heavy Loamy Sand	C	0.315	0	0.0618	1.225
6	Heavy Loamy Sand	Bg, Cg	0.298	0	0.0131	1.231
7	Heavy Loamy Sand	Go, Gr	0.351	0	0.0538	1.215
8	Silty Sand	Bg, Cg	0.288	0	0.00440	1.32
9	Sandy Loam	Bv, Bvt	0.363	0	0.0902	1.188
10	Sandy Loam	Bt, Bvg	0.279	0	0.00499	1.197
11	Sandy Loam	Bg	0.320	0	0.0341	1.132
12	Sandy Loam	C, Cc	0.322	0	0.0928	1.127
13	Sandy Loam	Cg	0.299	0	0.00185	1.154
14	Loam	Bvt	0.378	0	0.206	1.090
15	Loam	Bt	0.287	0	0.00451	1.142
16	Loam	Bg	0.290	0	0.00244	1.153
17	Loam	C, Cg	0.282	0	0.00185	1.154
18	Loamy Silt	C, Cc	0.382	0.0330	0.00622	1.344
19	Loamy Silt	Cg	0.361	0	0.00245	1.313
20	Silty Loam	C, Cc	0.367	0	0.00608	1.167
21	Silty Loam	Cg	0.363	0	0.00150	1.229
22	Silty Clay	Bvt	0.345	0	0.00157	1.160
23	Silty Clay	Bt, Bg	0.371	0	0.00090	1.160
24	Silty Clay	C, Cc, Cg	0.347	0	0.00038	1.222

SUMMARY

We have outlined methods for obtaining the unsaturated soil hydraulic parameters for a variety of applications, and shown the sensitivity of the predicted capillary rise to two hydraulic parameters. Experimental results of a sufficiently broad array of soil physical investigations should be included in a universal database. We recommend the use of classes of hydraulic properties to be defined on the basis of integral soil hydraulic properties. Each class should have typical hydraulic curves, with a corresponding characteristic set of hydraulic parameters.

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